PROCEEDINGS

55. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

13 - 17 September 2010

Crossing Borders within the ABC

Automation,

Biomedical Engineering and

Computer Science

Faculty of
Computer Science and Automation

www.tu-ilmenau.de

TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum
Published by

Publisher:	Rector of the Ilmenau University of Technology Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Editor:	Marketing Department (Phone: +49 3677 69-2520) Andrea Schneider (conferences@tu-ilmenau.de) Faculty of Computer Science and Automation (Phone: +49 3677 69-2860) Univ.-Prof. Dr.-Ing. habil. Jens Haueisen
Editorial Deadline:	20. August 2010
Implementation:	Ilmenau University of Technology Felix Böckelmann Philipp Schmidt

USB-Flash-Version.

Publishing House:	Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16 98693 Ilmenau
Production:	CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts
Order trough:	Marketing Department (+49 3677 69-2520) Andrea Schneider (conferences@tu-ilmenau.de)

ISBN: 978-3-938843-53-6 (USB-Flash Version)

Online-Version:

Publisher:	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=16739

THE INTELLIGENT CAR SEAT –MODEL BASE FOR COMFORT CONTROL OF ACTIVE CLIMATE SEATS

Carolin Zschippig B.Sc., Dipl.-Ing. Thomas Behrmann

Bremen Institute for Metrology, Automation and Quality Science, University of Bremen

ABSTRACT

To achieve optimal performance and traffic awareness, a driver has to feel comfortable in the car. One aspect for the comfort in a vehicle is the climate. Today, state-of-the-art cars feature automatically controlled climate in the passenger compartment, with individually set parameters for each car occupant. In addition, thermal comfort can be altered by manually controlled active climate seats. These seats are equipped with seat heating, typically electrical, and seat cooling, implemented using fans.

The thermal environment in the car cabin changes dynamically, due to various influences like direct solar irradiation. Since the seat is controlled manually, the seat occupant has to react to the changing climate. Due to the nature of human thermal sensation, the seat occupant will react only after an uncomfortable situation has already arisen. With a comfort control implemented in the seat, uncomfortable situations like sweat accumulation in the cloths could be prevented.

While the comfort sensation for static environments can be reasonably well predicted, there is still question as to how individuals percept dynamically changing thermal conditions. Which influence do the thermal control mechanisms of the human body have and how can these subjective comfort sensations be objectively measured? Can these parameters be measured non-invasively, without the car occupant having to place sensors actively onto the body?

The main issue of this paper is to analyze the contribution potential of car seat climate control to the provision of a comfortable thermal environment, in the face of dynamically changing boundary conditions. To achieve this, data of sensors embedded in the active climate seat is evaluated. The limitations and necessities for further research are evaluated.

Index Terms **–** Model based control, thermal comfort, climate, car seat, active climate seat

1. INTRODUCTION

The active control of the climate in buildings and vehicles has become a widely used technology. Much research has been done evaluating which factors influence the human comfort sensation [4], [15], [6]. When designing a climate control unit, it is of interest to predict how the people occupying the air-conditioned area will perceive the generated climate. One commonly used method to anticipate people's reactions is to calculate the Predicted Mean Vote, abbreviated PMV [6], which has been integrated into the EN ISO 7730 and the ASHREA Standard 55 [1], [3]. The calculation is based on a complete heat balance equation. Only if the body is in thermal equilibrium, meaning that the amount of heat created equals the amount of heat dissipated into the environment, the environment will be perceived as comfortable.

The PMV is an index, which rates the perceived thermal comfort on a seven-step scale:

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 1: Seven-step comfort scale

The calculated value represents the average response of a group of people in a steady state environment, given the following parameters are uniform and consistent for each person: metabolic rate M, clothing insulation I_{cl}, ambient air temperature ϑ_a, radiant temperature $\overline{\vartheta}_r$, air velocity v_a, humidity p_a.

From these values, firstly the clothing surface temperature is iteratively calculated, assuming the skin temperature is constantly 34°C. With the clothing temperature, the PMV is determined.

For a person sitting in a car seat, the insulation of the seat has to be taken into account when determining the heat loss of the body. The insulation values for body segments in contact with the seat differ from those exposed to air. In addition to that, the exposure of body segments to solar radiation is non-uniform. The calculation of the PMV does not permit differentiation between body segments within unequal climate conditions, but requires averaging the parameters. Also, it is explicitly stated in [1] that the PMV was deduced for constant conditions. If applied under dynamically changing conditions, it will only provide a valid approximation if the weighted mean of the last hour is used. This makes PMV too slow for an active climate control of a car seat.

2. EVALUATION OF COMFORT

An approach for determining the comfort in inhomogeneous environments is the equivalent temperature [8], [12]. The equivalent temperature is defined as: "The uniform temperature of the imaginary enclosure with a homogeneous temperature and air velocity equal to zero, in which a person will exchange the same dry heat by radiation, convection and conduction as in the actual non-uniform environment"(translated from [2]). Madsen et al. empirically derived an equation for the equivalent temperature [10], with the ambient temperature, the mean radiant temperature, the air velocity and clothing insulation as influencing variables. Since the equivalent temperature is defined for dry heat loss, humidity is not taken into account. Combining the influencing variables into a single parameter facilitates the comparison of different climate situations. The basis for the equivalent temperature concept is again a complete heat balance equation.

The equivalent temperature can also be measured, with a human-shaped, man-sized heated sensor, called thermal manikin. The body is divided into a number of segments, for each of which an equivalent temperature can be measured. The surface temperature of the heated sensor is controlled to a constant value of 34°C.

The equivalent temperature is a purely physical quantity, which does not take into account human perception. To determine whether a given equivalent temperature corresponds to a comfortable thermal environment, comfort zone diagrams have been developed, shown in Figure 1.

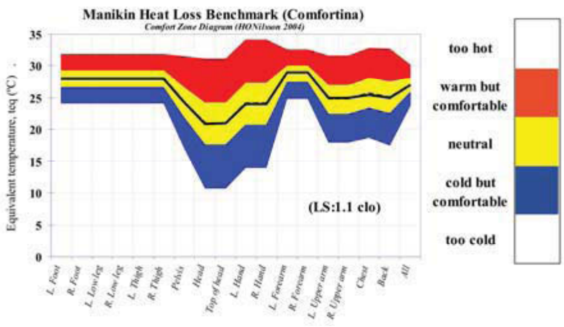

Figure 1: Comfort Zone Diagram

For a specific clothing insulation, measured in clo[1], the diagram depicts values of the equivalent temperature that were voted to be comfortable by test subjects.

[1] 1 clo = 0,155 m^2K/W

The equivalent temperature does not take into account evaporative heat loss due to sweat, or the influence of air humidity on the subjective comfort.

These facts pose limitations for the applicability of the equivalent-temperature-approach in the design of a control strategy for the active climate seat.

The neglect of evaporative heat loss and moisture in general prohibits the active compensation of sweat accumulation in the clothing and the seat, which is a major source of discomfort [5].

However, the influence of sweat and air humidity on the subjective comfort can be accounted for by including the evaporative heat loss into the heat balance equation. Since the comfort zone diagrams provide information on how an imaginary, uniform enclosure will be perceived, they can be used to predict the comfort vote in a real environment in which evaporation is not neglected. For this real environment, the amount of heat exchanged has to be determined, either through direct measurement or calculation.

While this solves the issue of inhomogeneity, there is still question to whether the comfort zones hold for dynamically changing conditions.

To address this issue, data was collected in experiments with test subjects. In these experiments, subjective responses to the corresponding climatic condition were recorded, along with heat flux density measurements between the body segments and the climate seat. At the same time, the possibility of a mathematical model which would be able to calculate the heat flux density was investigated, since the simulation of heat flux densities holds potential savings in the cost of the sensors implemented.

3. MATHEMATICAL MODELING

There are various mathematical models which describe physiological response of the human body to thermal conditions. These models claim to be able to predict heat flow within the body and between body and environment. They take into account dry as well as wet heat loss. The most prominent is the Stolwijk-Hardy-Model [15], which has been expanded, modified and taken as a basis for modeling by many different research groups [7], [9], [16], [13], [14], [11]. In addition to the parameters needed for the calculation of the PMV, these models require body-specific parameters as input. These include: mass, height, surface area, body fat percentage and cardiac output. Knowledge of these parameters allows a personalization of the model, incorporating individual differences. Some of these parameters can be measured unobtrusively or calculated from the data provided by the Seat-Position-Memory-System of the car, but not all. The body fat percentage and cardiac output require the placement of electrodes onto a person's body and are therefore not measurable in a car.

3.1. Model Constraints and Model Structure

The requirement for all input parameters to be measured unobtrusively limits the application of existing models. Dry and wet heat loss must be calculable without the use of body fat percentage and cardiac output. This can be achieved by incorporating the measurement of the surface temperature into the model. Body fat and cardiac output influence the skin temperature and consequently the surface temperature of the clothed body segments. The temperature of exposed skin and the surface temperature of clothed body segments can be measured unobtrusively in the car.

With the surface temperature known through measurement, the modeling of the internal heat flow from the core through muscle and fat tissue to the skin is no longer required.

The model implemented consists of geometric shapes, which abstract the surface of each body segment. The segments are: head, neck, chest, back, arm, front of thigh, back of thigh, shank and foot.

The 'back' and the 'back of thigh' segments are in direct contact with the seat. Figure 2 shows the layout of the segments.

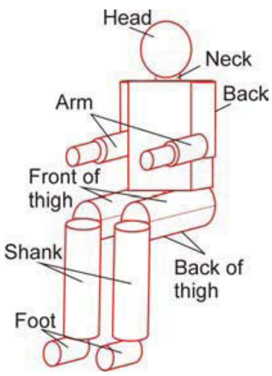

Figure 2: Geometric shapes of the modeled segments

Heat exchange with the environment is modeled taking into account convection, conduction, radiation and evaporation. The input parameters for each body segment of the model are: *air humidity, air temperature, body surface temperature, air velocity, solar irradiation, direction of the solar irradiation, mass, effective surface area coefficient* [17]. For body segments directly in contact with the active climate seat, the additional parameters *power of the seat heating* and *seat surface temperature* are required.

The model's structure is modular. Even though for the development of the seat control algorithm only body segments directly in contact with the seat have to be considered, all body segments were implemented. This allows a holistic analysis of the comfort perception with the option to evaluate the complete heat balance.

The heat flow due to convection, conduction and evaporation depend on the material properties and the design of the seat. In state of the art seats, the seat heating consists of a mesh of an electrically conducting material, like copper wire or carbon fibers, which convert electrical energy into heat. Cooling is implemented through ventilation. There exist two basic design concepts, differing in the direction of air flow. The air flow is directed either from the car compartment into the seat, as an impinging stream onto the underside of the seating surface and backrest, see Figure 3, or directed out of the seat into the passenger compartment.

In a series of pretests, seats of both designs were evaluated. The seats with the impinging stream showed a larger heat flow for the same power consumption and air speed. This design was chosen to be implemented in the model and to be used for further experiments.

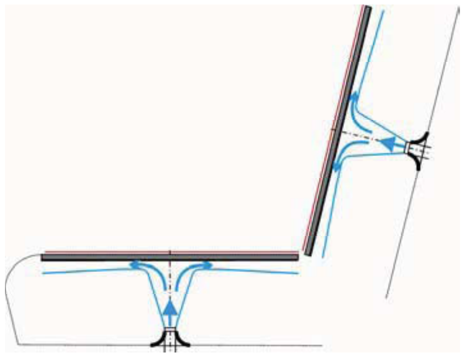

Figure 3: Impinging air stream onto the underside of the seating surface and backrest

4. EXPERIMENTS

Experiments with test subjects were performed to correlate heat loss with subjective response, to verify the usability of the comfort zone diagrams in dynamically changing conditions and to validate the mathematical model.

4.1. Setup

The experiments took place in a climatic chamber at Hohenstein Institute. Inside the chamber, a drive simulator was set up, where the test subject had to perform various driving tasks. Driving during the experiment ensured the metabolic rate of the test subject to equal a real driving condition. The subject was clothed in uniform standard attire, consisting of short underwear, jeans, long sleeve shirt and low shoes, with a combined insulation value of 1,1 clo.

Temperature, humidity and heat flux density was measured inside the seat and in the microclimate between skin and clothing of the test subject.

The active climate seat was equipped with an embedded system for measurement and control. It consisted of a host PC, a real time capable Simulink xPC-Target, a microcontroller AVR, a power controller for the heating and fans, and a total of 12 sensors measuring temperature, humidity and heat flux. A schematic overview can be seen in Figure 4.

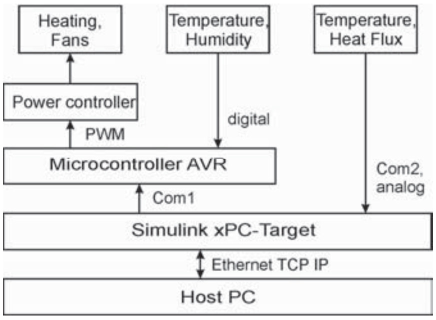

Figure 4: Schematic overview of the setup

A test subject was fitted with a total of 17 sensors, measuring the skin temperature, temperature and humidity in the microclimate and the heat flux density between body and seat.

The test subjects rated their subjective comfort sensation on the previously introduced 7-step scale, with 3 being the neutral, or comfortable, condition. To clarify the scale, the condition +1 was renamed: "warm, yet comfortable", and the condition -1 was renamed "cool, yet comfortable". The frequency of the comfort vote was $5min^{-1}$.

Inside the climatic chamber, a radiation wall was placed to simulate the asymmetric influence of solar radiation.

4.2. Execution

The experiment schedule was comprised of four sets, each evaluated with four male test subjects. The average age of the test subjects was 26 years (range 21 – 33) and their body mass index ranged from 18,8 to 25,2. The test subjects evaluated each set two times, on two separate days. The duration of an experiment was 180 minutes. The relative humidity inside the chamber was kept at a constant 50%, the ambient air velocity v_a was less than 0,15m/s, therefore not perceptible as draft. The parameters ambient air temperature ϑ_a and the mean radiant temperature $\bar{\vartheta}_r$ were dynamically changed. An overview of the parameters for each set can be seen in Table 2.

VR1	$\vartheta_a = \bar{\vartheta}_r$ = 35°C	cooling to	$\vartheta_a = \bar{\vartheta}_r$ = 15°C
VR2	$\vartheta_a = \bar{\vartheta}_r$ = 15°C	heating to	$\vartheta_a = \bar{\vartheta}_r$ = 35°C
VR3	$\vartheta_a = \bar{\vartheta}_r$ = 25°C	ϑ_a = 25°C,	$\bar{\vartheta}_r$ = 35°C
VR4	$\vartheta_a = \bar{\vartheta}_r$ = 20°C	ϑ_a = 20°C,	$\bar{\vartheta}_r$ = 35°C

t/min 0 20 40 60 80 100 120 140 160 180

Table 2: Experiment set schedule

In the first four sets, the boundary conditions of the climate chamber were varied. There was no heating or cooling within the seat. During the first 60min of the experiment, the conditions were kept constant. During the 61-120min of VR1 and VR2, the ambient air temperature was gradually altered to a new temperature level, which was then kept constant for the remaining 60 minutes.

The temperature gradient showed PT_1 behavior. In the sets V3 and V4 the radiation wall was utilized to simulate solar radiation, altering the radiant temperature without ambient air temperature change.

4.3. Results

The first step of the evaluation of the measured data was to find a correlation between the subjective comfort perception and heat loss.

The upper coordinate frame of Figure 7 shows the heat flux density measured in experimental set VR1. The lower coordinate frame shows the vote of the test subjects.

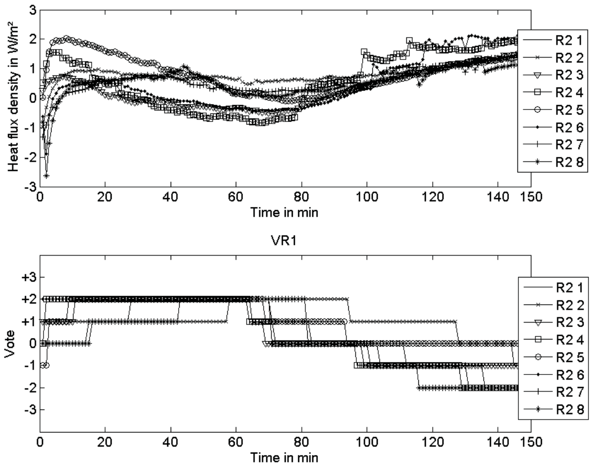

Figure 5: Heat flux density and comfort vote in VR1

Comparison of the heat flux density and corres-ponding votes during the steady state condition of the first hour of the experiment with the heat flux density and corresponding votes during the transient condition shows that equal heat flux values will evoke different comfort votes.

During the steady state condition of 35°C ambient air temperature, the heat flux density between body and seat decreases, while the test subjects vote the condition to be slightly warm to warm and mostly outside of the comfort zone. As the temperature is decreased to 15°C, starting at time 60min, the heat flux density begins to increase and the test subjects vote the condition to be neutral to cool. In Figure 6, the heat flux density with the corresponding comfort votes of the experiments 1 and 3 of VR1 are depicted in isolation as examples. It becomes evident that heat flux density values which were measured while the test subject voted the condition to be uncomfortably warm, are equal to values that were measured while the test subject voted the condition to be comfortable. When the heat flux density increases further (R1_3 after 100min), the comfort vote moves to the cool boundary of the comfort zone. The same value of heat flux density is placed within and outside of the comfort zone, depending on the boundary conditions.

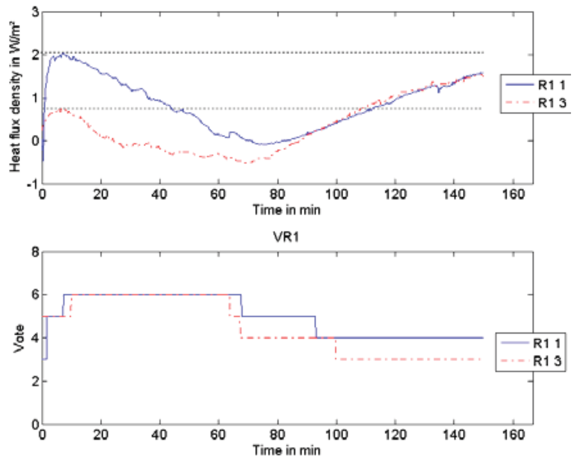

Figure 6: heat flux density and comfort vote in R1_1 and R1_3

This contradicts the assumption that the heat exchanged with the environment can be used as single determination factor of subjective comfort, independently of the climate conditions. These results were also found in the following experimental set.

Figure 7 shows the measured heat flux density and corresponding comfort votes for the experiment set VR2.

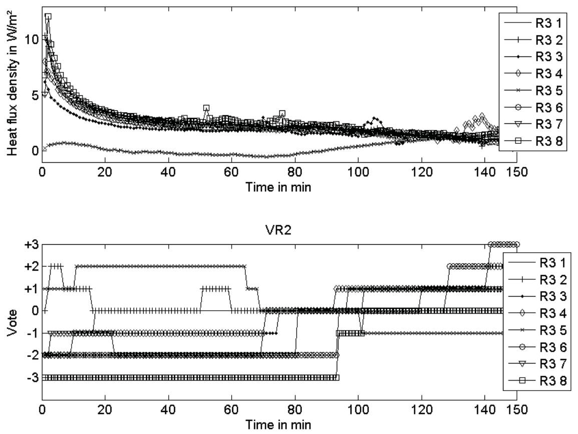

Figure 7: Heat flux density and comfort vote in VR2

During the timeframe 60min to 100min the climate condition changes distinctively, with the ambient air temperature rising logarithmically. This is traceable in the recorded comfort votes, which change from the negative range towards neutral and positive. However, the change is not evident in the measured heat flux density values.

As in experiment set VR1, equal heat flux values correspond to comfort votes within and outside of the comfort zone.

The simulated solar radiation in experiments VR3 and VR4 did not have any influence on the heat flux density between body and seat nor the comfort vote. Its influence could be traced in the measured values of the skin temperature of the body segments which were exposed to the radiation. The influence of the simulated solar radiation on the subjective comfort was not strong enough to alter the comfort vote for not directly exposed body segments.

A mathematical model was implemented in MATLAB/Simulink to calculate the heat flux density between body and environment. The model's simulation error lies within the specified tolerance for static and dynamic conditions with low perspiration rates. In conditions that evoke high perspiration, further improvements in the simulation of generated humidity are necessary to achieve desired accuracy.

5. CONCLUSION

The results of the experiments do not support the theory of comfort zone diagrams for dynamic conditions. The amount of heat exchanged between a body segment and the environment does not correspond to a distinct comfort sensation. This ambiguity prohibits the implementation of a single input control algorithm to achieve thermal comfort.

The results suggest that in transient conditions, the comfort sensation in single body segments is strongly influenced by the overall comfort sensation.

For example, the measurements of VR2 suggest people having difficulties evaluating thermal comfort sensations of different body segments independently. The sensation of the overall climate seems to influence the sensation of comfort in one segment, even though the segment is subject to different climate conditions.

The ambient air temperature in the climate chamber was 15°C for the first 60min of the experiment, then rising logarithmically to 20°C during the time 60min-75min. Since $\overline{\vartheta}_r = \vartheta_a$ and the ambient air velocity v_a was less than 0,15m/s, the equivalent temperature was also 15°C. This corresponds to an overall condition which will be voted too cold when dressed in clothing with an insulation value of 1,1 clo (compare Figure 1). After time 85min, the ambient air temperature had risen to above 23°C, increasing the equivalent temperature to a level inside the comfort zone for static conditions. Even though the heat flux density values between body and seat showed little change, the test subjects voted the condition to be comfortable.

The reason for this could lie in the thermal control strategy for the human body. It is vital that the body core temperature is kept at constant value of about 37°C, regardless of the environmental condition. One of the actuators to achieve this is the deliberate variation of the skin temperature and skin moisture of different body segments. The variation does not have to be simultaneous for all body segments. The body's control strategy does therefore not require the individual segments to be in a thermal equilibrium with the environment, but to jointly achieve a thermal equilibrium for the whole body. While the body is adapting to a changing condition, it possibly assesses the sensation of individual segments differently, emphasizing on the overall situation.

6. OUTLOOK

To be able to develop a controller which will provide the seat occupant with a comfortable thermal environment at all times, further research is necessary into the dynamics of human comfort sensation. With the developed mathematical model, it is possible to calculate the over-all heat balance of the body. In further experiments it could be investigated, to which extend and with which time constants the variation of the climate around single body segments will lead to a comfortable sensation, if the over-all heat balance is kept. If active climate seats were integrated into the climate control of the passenger cabin, boundary conditions for all body segments can be altered to achieve optimal comfort.

7. ACKNOWLEDGEMENTS

The joint project was funded through the Federal Ministry of Economics and Technology and its AiF project management organisation (German Federation of Industrial Cooperative Research Associations Otto von Guericke) within the IGF program, as AiF-Project No. 14963.

8. REFERENCES

[1] EN ISO 7730:2005, "Ergonomie der thermischen Umgebung - Analytische Bestimmung und Interpretation der thermischen Behaglichkeit durch Berechnung des PMV- und des PPD-Indexes und Kriterien der lokalen thermischen Behaglichkeit.", 2005

[2] DIN EN ISO 14505-2:2006 "Ergonomie der thermischen Umgebung- Beurteilung der thermischen Umgebung in Fahrzeugen-Teil 2:Bestimmung der Äquivalenttemperatur." 2006

[3] American Society of Heating, R. a. A.-C. E., Inc. 2009 ASHRAE handbook fundamentals. Atlanta, GA., ASHRAE, 2009.

[4] T. Bedford, "Environmental Warmth and Human Comfort." British Journal of Applied Physics 1(2): 33-38. 1950.

[5] P. Bröde and B. Griefahn, "Kriterien zur Beurteilung der Komfortbeeinträchtigung durch Feuchte-Entwicklung auf Kfz-Sitzen unter Hitzebelastung." I. f. A. a. d. U. Dortmund, 2002.

[6] P. O Fanger, Thermal comfort: analysis and applications in environmental engineering. New York, McGraw-Hill. 1972.

[7] D. Fiala, K. J. Lomas, et al. "A computer model of human thermoregulation for a wide range of environmental conditions: the passive system." Journal of Applied Physiology 87(5): 1957-1972, 1999.

[8] I. Holmér, "Evaluation of vehicle climate." Environmental Ergonomics - The ergonomics of human comfort, health and performance in the thermal environment, Elsevier Ltd., 2005.

[9] C. Huizenga, Z. Hui, et al. "A model of human physiology and comfort for assessing complex thermal environments." Building and Environment 36(6): 691-699, 2001.

[10] T. Madsen, "Comparison between operative and equivalent temperature under typical indoor conditions." ASHRAE Transactions 90(1): 1077-1090, 1984.

[11] A. Munir, S. Takada, et al. "Re-evaluation of Stolwijk's 25-node human thermal model under thermal-transient conditions: Prediction of skin temperature in low-activity conditions." Building and Environment 44(9): 1777-1787, 2009.

[12] H. O. Nilsson, Comfort climate evaluation with thermal manikin methods and computer simulation models. Stockholm, Arbetslivsinstitutet., 2004.

[13] H. O. Nilsson, H. Brohus, et al. "CFD modeling of thermal manikin heat loss in a comfort evaluation benchmark test", Proceedings of Roomvent 2007

[14] M. Salloum, N. Ghaddar, et al. "A new transient bioheat model of the human body and its integration to clothing models." International Journal of Thermal Sciences 46(4): 371-384, 2007.

[15] J. Stolwijk, and J. D. Hardy "Temperature regulation in man — A theoretical study." Pflügers Archiv European Journal of Physiology 291(2): 129-162, 1966.

[16] S.-i. Tanabe, K. Kobayashi, et al. "Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD)." Energy and Buildings 34(6): 637-646, 2002.

[17] S.-i. Tanabe, C. Narita, et al., "Effective radiation area of human body calculated by a numerical simulation." Energy and buildings. 32(2): 205, 2000.